

Determination of Moisture Content and Bulk Density of Shelled Corn by Measurement of Microwave Parameters

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Simultaneous measurement of two electromagnetic wave parameters (magnitude and phase change) of the wave transmitted through a layer of grain permits two variables of the grain (water concentration and dry grain density) to be determined. Knowledge of these two variables permits the calculation of moisture content and grain bulk density in real time. Although static experiments carried out at 9.4 GHz are described in the paper, the results and the method can be applied in dynamic measurements of flowing grain. The measurement does not require any contact between the material and the equipment, is fast, continuous and non-destructive. Uncertainty in static calibration for shelled corn (maize) is $\pm 0.56\%$ moisture and $\pm 25.1 \text{ kg} \cdot \text{m}^{-3}$, moist grain density, at the 95% confidence level.

Notation

α	attenuation constant
β	phase constant
γ	propagation constant
δ	measurement error
ϵ^*	complex relative permittivity
ϵ'	permittivity (dielectric constant)
ϵ''	loss factor
ξ	moisture content, m.c.
η	parameter
κ	parameter
λ	wavelength
λ_0	free space wavelength
μ^*	complex relative permeability
ρ	material density
σ	measurement uncertainty
τ	transmission coefficient
ϕ	phase angle

$\Delta\phi$	error in phase angle measurement
Φ	function
Ψ	function
ω	angular frequency
$a, b, c, d,$	
e	numerical constants
A	attenuation in dB
ΔA	error in attenuation measurement
c	velocity of wave propagation
f	frequency (c/λ_0)
k	water concentration
m_d	mass of dry material
m_w	mass of water
Δm	error in mass measurement
M	moisture content (w.b.) in %
n	integer
P	power
r	correlation coefficient
t	material layer thickness
T	complex transmission coefficient
v	volume
Δv	error in volume measurement
x	coordinate, distance

1. Introduction

Moisture content of grain is one of the most important factors that determines grain quality during processing, storage and transport. Usually, the moisture content, M , in per cent (wet basis), is defined as

$$M = \frac{m_w}{m_w + m_d} \times 100 = 100\xi \quad (1)$$

where m_w is the mass of water, m_d is the mass of dry material, and ξ is the fractional moisture content determined on a wet basis. For a given volume of

material, v , Eqn (1) may be rewritten in the form

$$\zeta = \frac{\frac{m_w}{v}}{\frac{m_w}{v} + \frac{m_d}{v}} = \frac{k}{\rho}, \quad (2)$$

where k is the water concentration in mass per unit volume, and ρ is the bulk density of the moist material. Some useful relationships may be obtained from Eqn (2), namely

$$k = \frac{m_w}{v} = \rho\zeta \quad \text{and} \quad \frac{m_d}{v} = \rho(1 - \zeta) \quad (3)$$

which will be used later.

Standard methods of moisture content determination are based on the definition, Eqn (1), and require determination of both components, m_w and m_d . Separation of these two components for grain can be achieved by various methods, such as water evaporation, extraction or distillation. Each of these methods requires a long time for completion (up to 72 h for oven drying of whole-kernel corn), and results are obtained for one or several samples of a few grams each. Because of the high variation in water (moisture) distribution in large grain lots in elevators, ships, or mill storage, many samples must be measured for reliable determination of moisture content.

In practice, there is need for a fast method of moisture content determination that would allow a much larger amount of grain (ultimately all of it) to be monitored. Such a moisture monitoring method should be non-destructive and non-contaminating. Over many years, electrical methods of indirect moisture content measurement have been developed, based on the correlation between electrical properties of grain and its moisture content.¹ As already noted,^{2,3} in the beginning the measured variable was direct current resistance. Later, radio frequency (RF) capacitance was used, and more recently microwave attenuation by the grain sample has been used.^{4,5} The increase in the frequency of the signals used for this purpose results in some advantages related to the interaction with water and gradual development of appropriate instrumentation as discussed elsewhere.^{6,7}

Changes of an electrical signal interacting with a moist material, regardless of operating frequency, are proportional to the water concentration, k , and are affected only to a small extent by the mass of dry material, m_d . Thus, while k can be determined from electrical measurements, it is evident from the definition of moisture content, Eqn (2), that determination of moisture content, ζ , requires the

density of the wet material, ρ , to be known. With laboratory batch-sample instruments, this requirement is often overcome by measuring a sample of given mass or of constant volume, but for on-line equipment, the information can only be obtained from a separate density measurement, for example, by using a γ -ray density gauge.⁸

Microwave moisture meters developed several years ago for various materials, including grain,^{4,9} permit non-destructive testing of significant amounts of material being transported from one place to another. The measurement takes place without any contact between the instrument and the material, and the results relate to an average moisture content of the material through which microwaves pass. Microwave methods are insensitive to differences in the water distribution in the grain kernels. Okabe *et al.*¹⁰ showed that for rice dried for a short time with hot air, moisture meters based on conductivity measurement (at 200 Hz) and on capacitance measurement (at 10 MHz) required sample conditioning for 10 and 6 h, respectively, before correct indications were given of average grain moisture content. A microwave meter operating at 9.4 GHz indicated the correct value of moisture content within 1 h, because its operation was not affected by water migration from the interior of the kernels to the dried surface. Measurements of the dielectric properties of wheat after disrupting kernel moisture equilibrium by surface wetting or drying¹¹ also showed that measured properties were nearly constant with time at 2.45 GHz, whereas, several hours were required for stabilization at 1 and 18 MHz.

The absorption and the phase shift of microwave radiation passing through a layer of moist material are caused by the water in its different states, e.g., cell water, surface water, bound water, free water, etc. Each state of water acts in a different way depending on the operating frequency.¹² In any case, the measured result is a function of the amount of water in the material layer. In the lower frequency range, the electrical properties of many organic materials are influenced by ionic conductivity (salt content) and bound-water relaxation. All these effects have nearly disappeared at frequencies above 5 GHz. Therefore, microwave moisture meters should preferably operate above this frequency.

Sekanov *et al.*¹³ indicated that errors of RF capacitive moisture meters due to the grain origin and cultivar variation may amount to 1.4% moisture content. Differences in the type of grain (hard or soft wheat) may account for errors up to 1%, and the year of harvesting may account for errors of 0.7–1.5% moisture content. In addition, the readings of capacitive moisture meters may depend upon the

nature and degree of grain impurities, type of moisture (natural or added), and on granular geometry and grain composition as indicated by the test weight.¹³ It is expected that some of these effects are related to differences in ionic conductivity and therefore could be limited by using microwave measurement methods.

It is the purpose of this paper to discuss principles of simultaneous moisture content and density determination in grain by microwave measurement techniques and to report results of recent experiments with these techniques. Although the results reported are for measurements on static samples of corn, these findings should also be applicable to on-line dynamic measurements of flowing grain.

2. General considerations

2.1. Wave interaction with matter

The dispersion and dissipation of electromagnetic waves interacting with a layer of dielectric material depend upon dimensions and the relative permittivity (dielectric properties) of the material. It is assumed that a linearly polarized, uniform plane wave of angular frequency, ω , is normally incident on the flat surface of a homogeneous material and that the planar sample is of infinite extent laterally so that diffraction effects at the edges can be neglected. When moisture content in the material changes, a change is reflected in the material permittivity, and that in turn affects the wave parameters. Because the relative permittivity of water (in its free state or bound to the matrix of hygroscopic material) differs greatly from that of most dry hygroscopic dielectric materials, its effect can be separated from the effect of the dry material. In general, it may be expressed in functional form as:

$$\kappa = \Phi_1\left(\frac{m_w}{v}, \frac{m_d}{v}\right) \quad \text{and} \quad \eta = \Phi_2\left(\frac{m_w}{v}, \frac{m_d}{v}\right) \quad (4)$$

where κ and η can represent any two descriptive electromagnetic wave parameters.

It has been shown^{14,15} that regardless of the complexity of the analytical expressions described by Eqn (4), it is generally possible to solve the two equations and to express the water concentration and the density of dry material in terms of two measured wave parameters in the form:

$$\frac{m_w}{v} = \Psi_1(\kappa, \eta) \quad \text{and} \quad \frac{m_d}{v} = \Psi_2(\kappa, \eta). \quad (5)$$

Substituting the analytical expressions corresponding to Eqn (5) into Eqn (2), the general expression for

moisture content of the material can be written as:

$$M = \frac{\Psi_1(\kappa, \eta)}{\Psi_1(\kappa, \eta) + \Psi_2(\kappa, \eta)} \times 100 \quad (6)$$

which contains only the wave parameters, determined experimentally, and is totally independent of the material density as well as the thickness of the layer of material. Moreover, combination of Eqns (2) and (5) provides the value of the material density for the layer in the form:

$$\rho = \frac{m_w + m_d}{v} = \Psi_1(\kappa, \eta) + \Psi_2(\kappa, \eta). \quad (7)$$

The bulk density of grain depends upon kernel shape, dimensions, temperature, moisture content and surface structure and conditions. Changes or fluctuations in the grain bulk density produce effects on measured wave parameters similar to those caused by changes in water content, creating moisture measurement errors. Providing a constant density of grain during continuous moisture content measurement under grain elevator or mill conditions is a very difficult problem. Various ways of limiting the density-variation effect in grain have been discussed recently,¹⁵ and it was concluded that the only reliable solution is the use of a *density-independent function*, e.g., a relationship between the dielectric properties of grain and its moisture content, similar in general to that expressed by Eqn (6). This concept has been developed further for use with wheat.¹⁶⁻¹⁸ In this paper, we present not only a method for determining grain moisture content independent of bulk density, but also a method for simultaneously determining the bulk density, which may be used for further correction if necessary. Verification of these considerations with experimental data for shelled corn of different hybrids is also provided in this paper.

2.2. Layer of a material in free-space

The two most frequently used parameters of a wave travelling through a layer of material in free-space are the magnitude and phase of the transmission coefficient expressed as

$$T = \exp(-\gamma t) = |\tau|e^{-j\phi} \quad (8)$$

where $|\tau|$ is the modulus of the transmission coefficient, ϕ is its phase angle, γ is the wave propagation constant, which for dielectric materials with magnetic permeability $\mu^* = 1$, is defined as

$$\gamma = \alpha + j\beta = \gamma_0 \sqrt{\epsilon^*} = j \frac{2\pi}{\lambda_0} \sqrt{\epsilon' - j\epsilon''} \quad (9)$$

where α is the attenuation constant, β is the phase constant, the relative complex permittivity of the material $\epsilon^* = \epsilon' - j\epsilon'' = \epsilon' - j\frac{\sigma}{\omega\epsilon_0}$, where σ is the material conductivity, $\omega = 2\pi f$ is the angular frequency, $\epsilon_0 = 8.854 \times 10^{-12}$ F/m is the permittivity of free space, the propagation constant of free space $\gamma_0 = j(2\pi/\lambda_0)$, λ_0 is the free-space wavelength, and t is the thickness of the material layer. To compute the modulus of the transmission coefficient, the initial and final amplitude measurements are utilized for the measuring space without and with the material. From basic electromagnetic theory¹⁹ it is well known that the power that propagates through a material must decrease according to the factor $e^{-2\alpha t}$. Referring to Fig. 1, if the power at $x=0$ is P_0 , then at $x=t$ the power is given, assuming no reflection, by

$$P = P_0 e^{-2\alpha t}.$$

The total decrease in power expressed in decibels is called the *attenuation*, and is given as

$$A = -20 \log |\tau| = -10 \log \left(\frac{P}{P_0} \right) = -10 \log (e^{-2\alpha t}). \quad (10)$$

The *phase shift* introduced by the layer of material is determined from the initial and final measurements of the wave phase angle in the reference plane, $x=t$. The initial phase measurement, ϕ_0 , is related to the phase constant, β_0 , and the thickness, t , of the free space through which the electromagnetic waves travel, as shown in Fig. 1, by

$$\phi_0 = \beta_0 t \quad (11)$$

assuming normal incidence. In a similar way, the final phase measurement is related to the phase constant, β_1 , and the thickness of material t by

$$\phi_1 = \beta_1 t. \quad (12)$$

The change in phase angle caused by introducing the material layer in the path of the travelling electromagnetic wave can be written as

$$\phi = \phi_1 - \phi_0 = (\beta_1 - \beta_0)t. \quad (13)$$

Since the phase constant is defined as 2π radians per wavelength, it can be rewritten as

$$\phi = \left(\frac{2\pi}{\lambda} - \frac{2\pi}{\lambda_0} \right) t = 2\pi t \left(\frac{1}{\lambda} - \frac{1}{\lambda_0} \right). \quad (14)$$

Because of the periodic nature of the wave phase through a dielectric medium, multiples of π or $2\pi n$ in phase, where n is an integer, can exist for a sample of

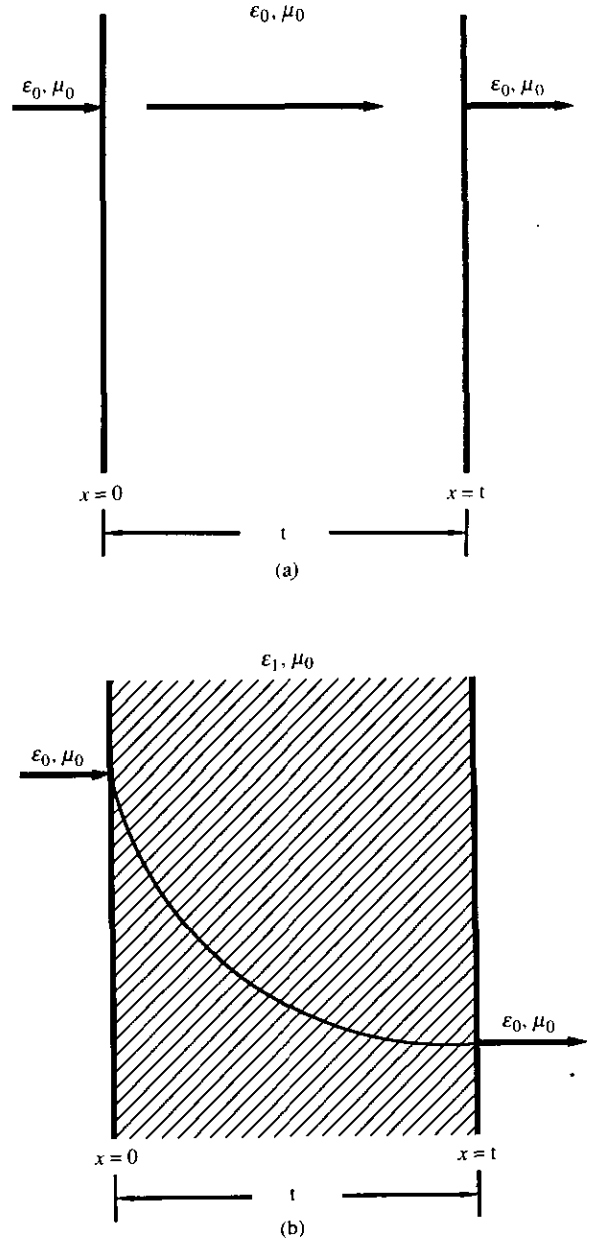


Fig. 1. Uniform plane waves normally incident upon (a) free space and (b) layer of dielectric material.

thickness t . Thus Eqn (14) in reality becomes

$$2\pi t \left(\frac{1}{\lambda} - \frac{1}{\lambda_0} \right) = \begin{cases} \pm 2\pi n \pm \phi \\ \pm 2\pi n \pm (\pi - \phi) \end{cases} \quad (15)$$

to account for all possible combinations. Since the wavelength, λ , within the dielectric material is smaller than the free-space wavelength, λ_0 , the left-hand side of Eqn (15) is always positive; hence, the right-hand side must also be positive for any n multiple of phase

angle. Therefore the constraints on Eqn (15) are

$$2\pi t \left(\frac{1}{\lambda} - \frac{1}{\lambda_0} \right) = \begin{cases} |\phi| \\ |\pi - \phi| \end{cases} \quad n = 0$$

$$\begin{cases} 2\pi n \pm \phi \\ 2\pi n \pm (\pi - \phi) \end{cases} \quad n = 1, 2, 3, \dots \quad (16)$$

Since there are numerous solutions to this equation, several samples of different thicknesses are used to resolve the phase-shift ambiguity.

3. Materials and methods

Two yellow-dent hybrids of field corn, *Zea mays* L., grown in 1989, FR 1141 × LH123 from Urbana, Illinois, and Crows 488 from Lincoln, Nebraska, were used for the calibration measurements. To provide a range of natural moisture contents, whole ears were harvested over several weeks from the same fields and sealed in plastic bags for shipment to Athens, Georgia. Upon arrival in Athens, all bags were stored at 4°C until used for measurements.

In preparation for tests, ear corn was shelled by hand, sealed in 4-l Mason jars, returned to 4°C storage and permitted to equilibrate for at least 7 d before any measurements were performed. Moisture content in early shipments was 32–35%, wet basis, while the last shipment of corn harvested in mid-October was 18–19% w.b. Samples of corn were allowed to dry in trays in the laboratory (23°C, 40% RH) for various time intervals to obtain desired moisture contents. Test weights were determined at various moisture levels with a standard weight-per-bushel apparatus along with microwave measurements. After every drying period, samples were sealed in the jar and stored at 4°C for at least 72 h to ensure uniform moisture distribution within the sample. Samples were stirred frequently by rotating the sealed jars to aid in uniform moisture distribution. Before every measurement session, jars were left in the laboratory for at least 24 h to allow the sample temperature to equilibrate with the environment.

Microwave measurements were carried out with the grain samples in a Plexiglas container. Starting from the natural bulk density, the measurements were repeated for samples of gradually increased density, which was obtained by shaking and settling the sample in the container. The whole volume of the container was always filled with grain, and the mass of the grain was recorded before every measurement. Moisture content of the sample was determined by a standard forced-air oven method²⁰ just after the microwave

measurements were finished. The 15 g whole-kernel corn samples were dried for 72 h at 103°C. An average uncertainty in the moisture content determination by the standard method was experimentally evaluated on triplicates as smaller than ±0.3% moisture.

Verification measurements were carried out 1 year later with three field corn hybrids: Northup King 7686 grown in Nebraska, Pioneer 3320 from Georgia and FR27rh × FRMO17rh grown in Illinois. As before, all samples were dried gradually from the natural after-harvest moisture content, and after every moisture change, samples were conditioned for 5–7 d at 4°C in sealed jars to restore uniform moisture distribution in the kernels and among the kernels in the sample. Test weights were also determined at several moisture levels.

During the microwave measurement procedure, the sample was held in a Plexiglas container of rectangular cross-section, 100 by 110 mm. A sample of corn weighing approximately 1.5 kg filled the box to a height of 160 mm. A block diagram of the measuring arrangement is shown in Fig. 2. Components of the transmission coefficient (attenuation and phase shift of the electromagnetic wave passing through the corn sample) were measured in free-space. The corn sample holder was located between two waveguide horn antennas (aperture dimensions 43 by 31.3 mm) that were connected to the transmitting—receiving system operating at 9.4 GHz. The uncertainties of the measuring system were evaluated experimentally as $\Delta A = \pm 0.25$ dB for the attenuation measurement and $\Delta \phi = \pm 3^\circ$ for the phase-shift measurement, including repeatability of measurement for several sample insertions during a short period of time. Although an automatic network analyser was used as a measuring system in these experiments, it could, without significant degradation of the measuring accuracy, easily be replaced by a simple two-parameter measuring set-up as, for example, that described previously.¹⁶

Fifty-one corn samples of different moisture contents were measured, ranging from 8.8 to 23.7% wet basis. Each sample was measured at four to seven densities, providing 257 data points for use in developing the calibration equations. During the verification process, similar measurements provided 323 data points.

4. Experimental results

Results of test-weight determinations for both calibration and verification lots of shelled corn are

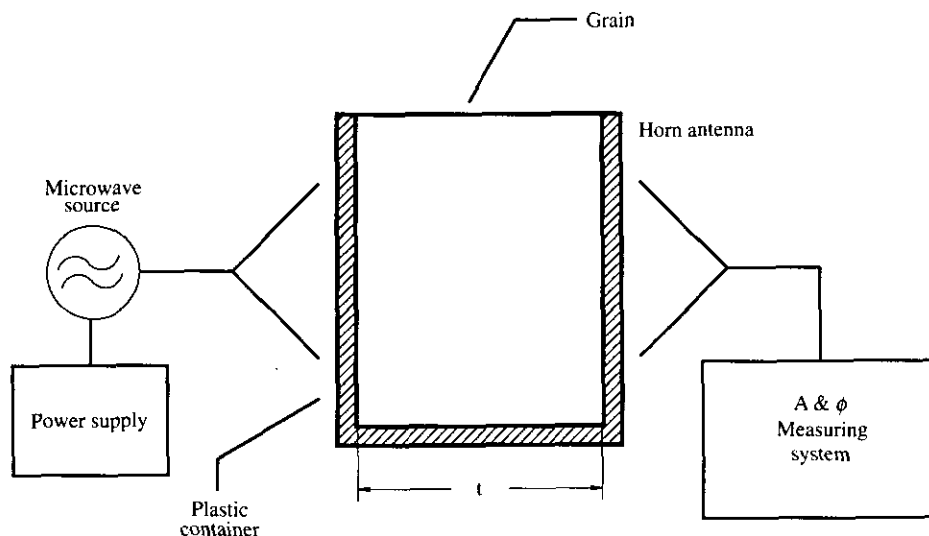


Fig. 2. Block diagram of the arrangement for free-space measurement of attenuation and phase shift of microwave signal transmitted through grain layer of thickness, t .

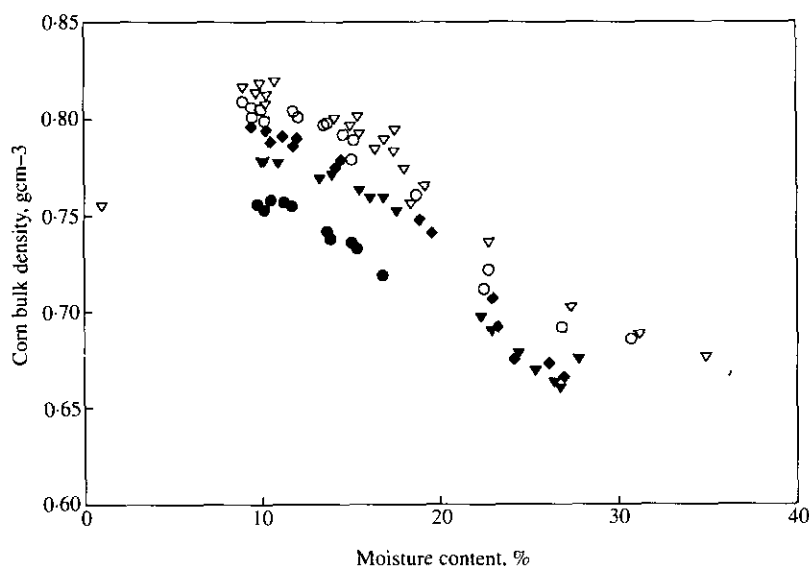


Fig. 3. Test weight (bulk density) for five corn lots at 23°C as a function of grain moisture content. ○, 1989; ●, 1990. Circles, Nebraska; triangles, Illinois; diamonds, Georgia.

shown in Fig. 3. Although the bulk-density dependence on moisture content is similar for all lots, there are differences between test weights of different lots. Generally, the 1989 lots had higher bulk densities than those harvested 1 year later.

The measurements for the 257 data points taken at 9.4 GHz included measured values of moisture content and density and also attenuation and phase shift of microwave signals after passing through the 10 cm thick layer of corn. The concentration of water and the dry material density were next calculated by Eqn (3). The attenuation of microwave signals as a function of water concentration is shown in Fig. 4 and

the phase shift as a function of water concentration is shown in Fig. 5, with density of dry material as a parameter. Two linear equations fit the experimental results with high statistical significance

$$A = 35.307 + 0.348 \frac{m_w}{v} - 0.0643 \frac{m_d}{v} \quad r = 0.9865$$

$$\phi = 4.892 \frac{m_w}{v} + 0.4922 \frac{m_d}{v} \quad r = 0.9996$$

(17)

where r is the correlation coefficient, and the concentration of water and density of dry grain are expressed in

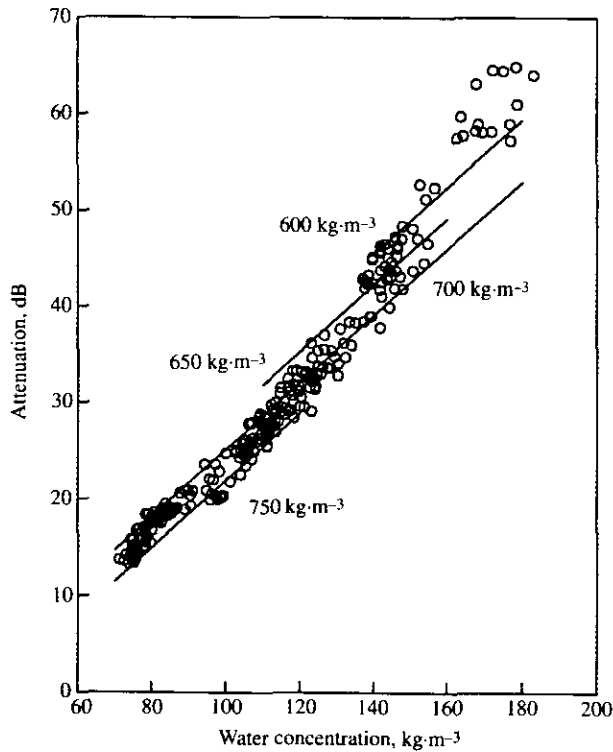


Fig. 4. Attenuation in shelled corn as a function of water concentration measured at 9.4 GHz and 23°C on layer of grain 100 mm thick. Lines are for constant values of dry-material density (m_d/v) indicated, as calculated from Eqn (17).

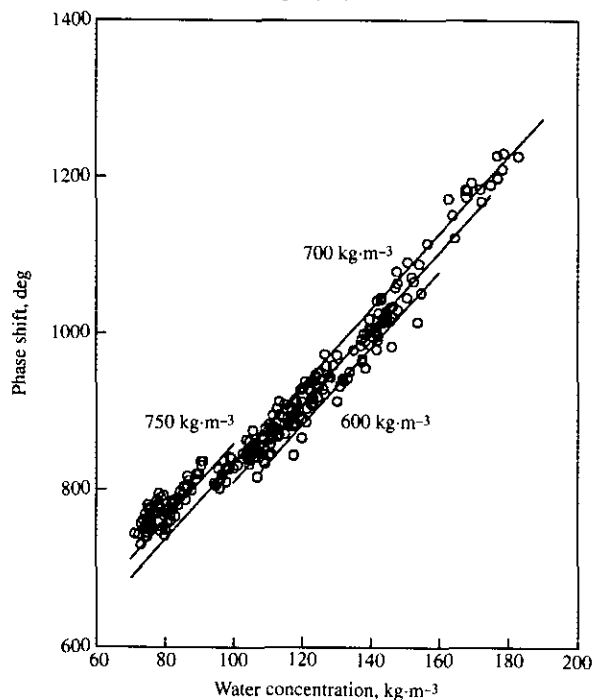


Fig. 5. Phase shift in shelled corn as a function of water concentration measured at 9.4 GHz and 23°C on layer of grain 100 mm thick. Lines are for constant values of dry material density (m_d/v) indicated, as calculated from Eqn (17).

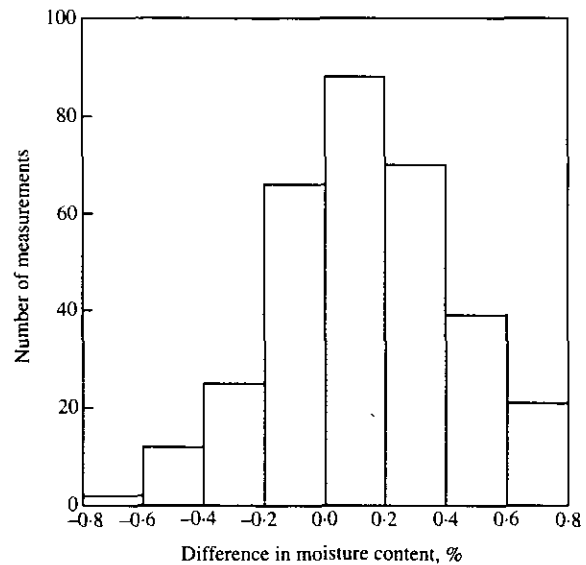


Fig. 6. Distribution of differences between oven moisture content determination and moisture content calculated for three lots of corn grown in 1990 from calibration equation, Eqn (18), for 323 measurements at 9.4 GHz.

$\text{kg} \cdot \text{m}^{-3}$. According to the theoretical considerations, use of Eqns (10) and (11) provides the expressions for the moisture content and bulk density in the form:

$$M = \frac{15.61\phi + 119.4A - 4215.7}{\phi - 10.674A + 376.86}, \quad (18)$$

$$\rho = 0.8483(\phi - 10.674A + 376.86). \quad (19)$$

Validity of the calibration equations was checked 1 year later with different corn lots. Samples of 43 different moisture contents ranging from 9.4 to 24.6% were measured with the same measuring set-up and the same procedures that were used for the calibration measurements. A total of 323 data points for various moisture contents and densities were obtained during these measurements. Data from these measurements were used in Eqns (18) and (19) to predict moisture content and corn bulk density, respectively. These values were compared with oven moisture tests and bulk density determinations from sample weights and sample holder volume. The histogram presented in Fig. 6 shows the distribution of differences between oven moisture-content determination and calculated moisture content for these data. The mean value of differences between oven moisture content and calculated moisture content (bias) was 0.135% moisture, while the standard deviation of the differences (standard error of performance, SEP) was 0.287% moisture. The relationship between the moisture content determined by the standard oven method and the moisture content of the grain of

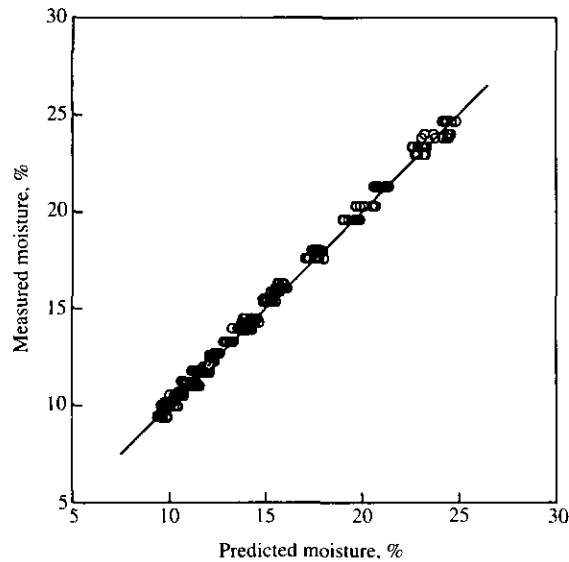


Fig. 7. Relationship between oven moisture content determination and moisture content calculated from calibration equation, Eqn (18), for three lots of corn grown in 1990.

arbitrary density predicted from the microwave measurements at 9.4 GHz [Eqn (18)] may be expressed in the form:

$$M_{\text{oven}} = 1.0066M + 0.038.$$

The graphical representation of this relationship is shown in Fig. 7 while in Fig. 8 the relationship between the measured grain density and the density predicted by Eqn (14) is shown. The straight lines in these figures indicate ideal agreement between the

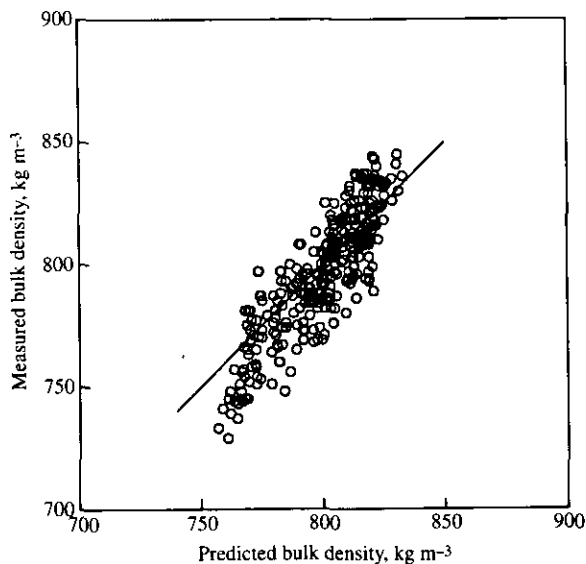


Fig. 8. Relationship between measured grain bulk density and the density predicted from calibration equation, Eqn (19), for three lots of corn grown in 1990.

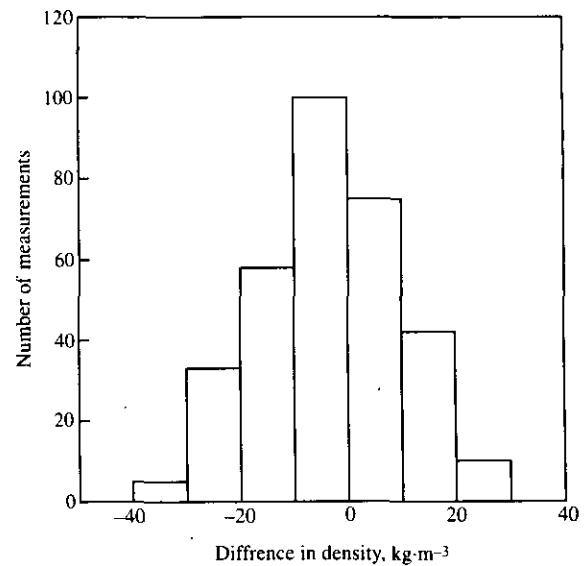


Fig. 9. Distribution of differences between measured corn bulk density and the density predicted from calibration equation, Eqn (19), for 323 measurements of three lots of corn at 9.4 GHz.

measured and calculated values. The relationship between the measured bulk density and the density of the grain predicted from the microwave measurements at 9.4 GHz [Eqn (19)] has the form:

$$\rho_{\text{exp}} = 1.188\rho - 153.9.$$

The standard error of performance for the bulk density determination is $25.1 \text{ kg} \cdot \text{m}^{-3}$, while the bias is $-3.6 \text{ kg} \cdot \text{m}^{-3}$. Distribution of differences between measured and predicted corn bulk densities is presented as a histogram in Fig. 9. It is evident from Figs 6–9 that the sign of the error is not related to the range of measured values of moisture contents and that the error distribution has totally random character in the case of both predicted variables.

5. Uncertainty analysis

The accuracy of the measuring instrument calibration is affected by an uncertainty of the measuring system, σ_M , consisting of the repeatability of the result for the same grain sample of given moisture content and the uncertainty of the moisture content determination by the standard method used, σ_c . Since both of the errors are of a random character, the uncertainty in using the microwave instrument for moisture content determination in corn may be defined as:

$$\sigma_s = \pm \sqrt{\sigma_M^2 + \sigma_c^2}. \quad (20)$$

The uncertainty in the measuring system can be

determined by differentiation of Eqns (18) and (19) in a general form:

$$M = \frac{a\phi + bA + c}{d\phi + eA + g} \quad \text{and} \quad \rho = d\phi + eA + g$$

which gives

$$\sigma_M = \frac{(ag - cd) + (ae - bd)A}{(d\phi + eA + g)^2} \Delta A + \frac{(bg - ce) + (ae - bd)\phi}{(d\phi + eA + g)^2} \Delta \phi \quad (21)$$

and

$$\sigma_\rho = \rho(d|\Delta\phi| + e|\Delta A|) \quad (22)$$

where ΔA and $\Delta\phi$ are the uncertainties in the measured wave parameters, expressed in decibels and in degrees, respectively.

The average spread in triplicate samples determined by the standard oven method was 0.176% moisture. This value was taken as an uncertainty of the standard method, σ_c . Taking the average values for ρ , A and ϕ in Eqn (21) together with experimentally determined values of errors and numerical coefficients from Eqns (18) and (19), one obtains $\sigma_M = 0.255\%$ and $\sigma_s = 0.310\%$ moisture from Eqn (20), which is to be compared with 0.287% moisture determined experimentally (see Fig. 5).

The uncertainty in the method of bulk density assessment by separate mass and volume determination may be expressed as

$$\sigma_d = \rho \left(\frac{\Delta m}{m} + \frac{\Delta v}{v} \right) \quad (23)$$

with $m = 1400$ g and $v = 1760$ cm³. The average error in bulk density determinations was $\sigma_d = 13.1$ kg m⁻³, which came from the uncertainty of ± 1 g in sample mass determination of 1400 g, and the uncertainty of ± 27.5 cm³ in sample volume measurement (one-half of the smallest corn kernel dimension, which was taken as 0.5 cm, at the 10 × 11 cm surface of the Plexiglas sample holder). Introducing the average values of ρ , A and ϕ into Eqn (22), one obtains $\sigma_\rho = 4.81$ kg m⁻³. The system uncertainty from Eqn (23) is 13.93 kg m⁻³ which is to be compared with 12.82 kg m⁻³ determined experimentally (see Fig. 9). These numbers confirm that reasonable values of uncertainties were assumed for the evaluation.

6. Discussion

Microwave measurement of moisture content in grain provided reliable results on several different

yellow-dent field corn hybrids grown in three widely different locations without need for changes in calibration. Earlier work indicated similar universality of calibration for wheat.^{18,21} The expected uncertainty for moisture measurement on shelled corn is 0.56% moisture content at the 95% confidence level, which can be compared with $\pm(1.7-2.0\%)$ obtained during more extensive tests of capacitive moisture meters¹³ in a similar range of moisture content. The moisture content determination is totally independent of grain bulk density, and the mass of the sample is irrelevant. Furthermore, by measuring two electromagnetic wave parameters (magnitude and phase shift of the wave transmitted through the layer of material), two variables of the grain sample can be determined (water concentration and dry grain density). Knowledge of these two variables permits real-time calculation of both moisture content and bulk density of the grain with simple calibration equations, e.g., Eqns (18) and (19). Because both measured quantities relate to a grain layer of the same thickness, the calibration equations can be simultaneously solved without explicit knowledge of the material thickness.

Although measurements on static samples are described in the paper, the principles are applicable to a dynamic moisture determination in a flowing stream of grain (in a pipe, chute or conveyer). The measurement does not require any contact between the material and the equipment; thus it can be fast, continuous, and non-destructive. Microwave moisture measuring instruments could be applied during grain tempering before milling, or in grain drying after harvest. On-line measurements could be used for automatic control of water sprinklers or of the fuel supply to the drier burner.

Until now, applications of microwave methods for moisture content measurement have been limited because of relatively high costs of equipment. In the past few years, prices of components, devices and systems have been significantly reduced; thus, microwave moisture meters may now be produced at prices more nearly competitive with conventional capacitive moisture meters, in view of the advantages offered.

7. Conclusions

Simultaneous measurement of the attenuation and phase shift of microwaves traversing a layer of grain can be used for instantaneous determination of both moisture content and bulk density. Such determinations were made on shelled corn (maize) lots from

widely separated locations in the USA with uncertainties of 0.56% moisture content and 25 kg cm^{-3} wet bulk density at the 95% confidence level.

The microwave measurement technique offers advantages that include a density-independent determination of moisture content, bulk density determination, insensitivity to moisture distribution within the kernel, elimination of ionic conductivity effects, and a non-contacting, non-destructive, instantaneous measurement.

Although the principles demonstrated were verified with 9.4 GHz measurements on static samples, the principles should be applicable to dynamic conditions and therefore useful for measurements on flowing grain.

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